An Algorithm for Determining the Load Margin of an Interconnected Power System

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Abstract- **The paper describes a new method for determining critical load for a bus with respect to its voltage collapse limit of an interconnected multi-bus power system. For this purpose, network partitioning technique is used to transform load flow Jocobian matrix into a two by two matrix with respect to a selected/target bus and a procedure has been developed to determine load margin of the target bus using the elements of the transformed two by two elements Jacobian matrix and the bus voltage of the target bus. The validity of the proposed method has been investigated for the IEEE 30 and IEEE 118 bus systems.**

Keywords- Voltage Stability; Load Margin; Voltage Collapse; Power System

List of Symbols:

N = Total number of buses in the system.
NG = Total number of generation buses in the system.
P_i = Injected active power at ith bus.
Q_i = Injected reactive power at ith bus.
P_{Di} = Active power demand at ith bus.
Q_{Di}= Reactive power demand at ith bus.
P_{Gi} = Active power generated by ith generator.
Q_{Gi} = Reactive power generated by ith generator.
Vi = Magnitude of voltage at ith bus.
δi = Angle of the bus voltage at ith bus.
cos Ø = Load power factor of the ith load bus.
$G_{ij} + j B_{ij}$ = Element of Y-BUS matrix at ith row and jth column.

I. INTRODUCTION

The voltage instability of an interconnected power system is a major concern for the power system operator and planner. It has been observed that voltage magnitudes in general, do not give a good indication of proximity to voltage stability limit [1]. In recent literature several voltage stability and voltage collapse prediction methods have been presented. Some of the important ones are: voltage collapse index based on a normal load flow solution [2, 3, 4], voltage collapse index based on closely located power-flow solution pairs [5], voltage collapse index based on sensitivity analysis [6], and minimum singular value of Newton - Raphson power flow Jacobian matrix [7, 8]. Continuation power flow analysis is based on locally parametrized continuation technique; it aims at avoiding the singularity of the Jacobian by slightly reformulating the power flow equations [9]. Network partitioning technique has been employed for investigating voltage stability condition of a load bus [10]. A simple, computationally very fast local voltage-stability index has been proposed using Tellegen's theorem [11]. It is easy to implement in the wide-area monitoring and control center or locally in a numerical relay. A new node voltage stability index called the equivalent node voltage collapse index (ENVCI), which is based on ESM and uses only local voltage phasors, is presented [12]. Information/knowledge of load margin of a bus with respect to its voltage collapse limit constitutes an important criterion for load pick-up step during power system restoration planning and operation. The bus having highest load margin appears to be the best choice [13] for load pick-up and magnitude of load to be picked-up must be less than the load margin for a bus.

A method has been proposed in reference [14] to determine load margin of a target bus by transforming the load flow jacobian matrix of a multi-bus system into a two by two matrix with respect to the target bus. But, the transformation step uses sensitivity relation which depends on decoupled basis (simplification). In addition to this, the perdition step uses an empirical formula to normalize the effect of linear representation of the sensitivity relations. As a result, the perdition defers from actual value when perdition is made at a point which is not near to the proximity of voltage collapse. This is the major disadvantage of the work and therefore, it is not reliable for practical use. This paper proposes an algorithm for determining the load margin of a selected/target bus with respect to its voltage collapse limit using the two by two matrix created by network partitioning technique. The use network partitioning technique eliminates the simplification adopted in the reference [14] while transforming the load flow jacobian matrix of a multi-bus system into a two by two matrix with respect to the target bus. Also, the paper introduces a full algorithm for the determination of load margin irrespective of working point of the power system. Two factors namely RF(Reduction Factor) and DF(Distance Factor) have been introduced for this propose. This allows the incorporation of a correction load flow step after perdition step.

II. VOLTAGE STABILITY CRITERIA: NETWORK PARTITIONING TECHNIQUE

The determinant of load flow Jocobian matrix reduces as an interconnected power system approaches the proximity of voltage collapse and it becomes zero when the system arrives at the point of voltage collapse. Network partitioning techniques [10] is used to transform a load flow Jocobian matrix into a two by two matrix with respect to a selected/target bus. As such, when this two by two matrix becomes zero, the system voltage collapse occurs.

The liberalized system of load flow equation for an interconnected power system is represented as:

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} E & F \\ G & H \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta V \end{bmatrix} \qquad (1)$$

, where E, F, G and H corresponds to the load flow Jocobian of the system. Rearranging items by putting the equations dealt with the bus under analysis (selected/target kth bus) to the bottom of the Jacobian matrix, we have,

$$\begin{bmatrix} \Delta P' \\ \Delta Q' \\ \Delta P_k \\ \Delta Q_k \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta V \\ \Delta\delta_k \\ \Delta V_k \end{bmatrix} \qquad (2)$$

, where- sub matrices A, B, C, D is originated from the system Jocobin matrix. It is assumed that the active power and reactive power of all the load (or generator) keep constant except for selected/target kth bus, i.e., **ΔP' =0, ΔQ'=0**, the matrix represented by Equation (2) is simplified as [10]:

$$\begin{bmatrix} \Delta P_k \\ \Delta Q_k \end{bmatrix} = \left[\begin{bmatrix} \frac{\partial P_k}{\partial \delta_k} & \frac{\partial P_k}{\partial V_k} \\ \frac{\partial Q_k}{\partial \delta_k} & \frac{\partial Q_k}{\partial V_k} \end{bmatrix} \right] \begin{bmatrix} \Delta\delta_k \\ \Delta V_k \end{bmatrix} \qquad (3)$$

, where

$$\begin{bmatrix} \frac{\partial P_k}{\partial \delta_k} & \frac{\partial P_k}{\partial V_k} \\ \frac{\partial Q_k}{\partial \delta_k} & \frac{\partial Q_k}{\partial V_k} \end{bmatrix} = D - CA^{-1}B \qquad (4)$$

III. DETERMINATION OF LOAD MARGIN

Equation (3) can be represented as two bus system with the target kth load bus, Y-Bus elements and an equivalent source as depicted in Figure 1.

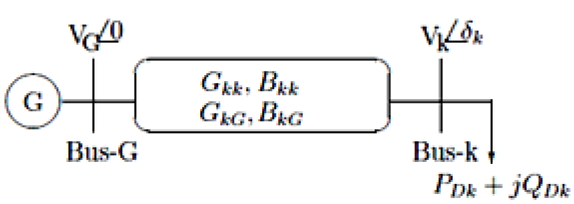

Figure 1: Equivalent two bus system with target *kth* bus Y-Bus elements and an equivalent source.

The expression for real and reactive power injections at the target kth bus of the equivalent two bus system can be expressed as:

$$P_k = G_{kk}V_k^2 + V_G V_k (G_{kG}cos(\delta_k) + B_{kG}sin(\delta_k)) \qquad (6)$$
$$Q_k = -B_{kk}V_k^2 + V_G V_k (G_{kG}sin(\delta_k) - B_{kG}cos(\delta_k)) \qquad (7)$$

, where- G_{kk}, B_{kk}, G_{kG} and B_{kG} are the elements of admittance matrix [Y] for the equivalent two bus system.

The elements of Jacobian matrix for the equivalent two bus system can be expressed as

$$\frac{\partial P_k}{\partial \delta_k} = V_G V_k(-G_{kG}sin(\delta_k) + B_{kG}cos(\delta_k)) \qquad (8)$$
$$\frac{\partial P_k}{\partial V_k} = 2G_{kk}V_k + V_G(G_{kG}cos(\delta_k) + B_{kG}sin(\delta_k)) \qquad (9)$$
$$\frac{\partial Q_k}{\partial \delta_k} = V_G V_k(G_{kG}cos(\delta_k) + B_{kG}sin(\delta_k)) \qquad (10)$$
$$\frac{\partial Q_k}{\partial V_k} = -2B_{kk}V_k + V_G(G_{kG}sin(\delta_k) - B_{kG}cos(\delta_k)) \qquad (11)$$

At the point of voltage collapse the determinant of the Jacobian matrix becomes zero, i.e.,

$$Det|J| = J_D = \frac{\partial P_k}{\partial \delta_k}\frac{\partial Q_k}{\partial V_k} - \frac{\partial P_k}{\partial V_k}\frac{\partial Q_k}{\partial \delta_k} = 0 \qquad (12)$$

The change in determinant value of the two bus equivalent system of the multibus system with respect to change in $\mathbf{V_k}$ and $\boldsymbol{\delta_k}$ can be expressed as

$$\Delta J_D = \frac{\partial J_D}{\partial \delta_k}\Delta\delta_k + \frac{\partial J_D}{\partial V_k}\Delta V_k = \begin{bmatrix} \frac{\partial J_D}{\partial \delta_k} & \frac{\partial J_D}{\partial V_k} \end{bmatrix} \begin{bmatrix} \Delta\delta_k \\ \Delta V_k \end{bmatrix} \qquad (13)$$

Again, the expression for J_D in terms of $\frac{\partial P_k}{\partial \delta_k}$, $\frac{\partial Q_k}{\partial V_k}$, $\frac{\partial P_k}{\partial V_k}$ and $\frac{\partial Q_k}{\partial \delta_k}$ is as follows

$$J_D = \frac{\partial P_k}{\partial \delta_k}\frac{\partial Q_k}{\partial V_k} - \frac{\partial P_k}{\partial V_k}\frac{\partial Q_k}{\partial \delta_k} \qquad (14)$$

Therefore, $\frac{\partial J_D}{\partial \delta_k}$ can be expressed as

$$\frac{\partial J_D}{\partial \delta_k} = \left[\frac{\partial P_k}{\partial \delta_k}\frac{\partial \frac{\partial Q_k}{\partial V_k}}{\partial \delta_k} + \frac{\partial Q_k}{\partial V_k}\frac{\partial \frac{\partial P_k}{\partial \delta_k}}{\partial \delta_k}\right] - \left[\frac{\partial P_k}{\partial V_k}\frac{\partial \frac{\partial Q_k}{\partial \delta_k}}{\partial \delta_k} + \frac{\partial Q_k}{\partial \delta_k}\frac{\partial \frac{\partial P_k}{\partial V_k}}{\partial \delta_k}\right] \quad (15)$$

The terms $\frac{\partial \frac{\partial Q_k}{\partial V_k}}{\partial \delta_k}$, $\frac{\partial \frac{\partial P_k}{\partial \delta_k}}{\partial \delta_k}$, $\frac{\partial \frac{\partial Q_k}{\partial \delta_k}}{\partial \delta_k}$ and $\frac{\partial \frac{\partial P_k}{\partial V_k}}{\partial \delta_k}$ are derived utilizing Equations (8) to (11). It is to be ensured that these terms contain only the element of the modified two by two element Jacobian matrix and the bus voltage of the target bus, because,- they are the known values for the transformed two by two systems.

$$\frac{\partial \frac{\partial Q_k}{\partial V_k}}{\partial \delta_k} = V_G(G_{kG}cos(\delta_k) + B_{kG}sin(\delta_k)) = \frac{\frac{\partial Q_k}{\partial \delta_k}}{V_k} \quad (16)$$

$$\frac{\partial \frac{\partial P_k}{\partial \delta_k}}{\partial \delta_k} = -V_G V_k(G_{kG}cos(\delta_k) + B_{kG}sin(\delta_k)) = -\frac{\partial Q_k}{\partial \delta_k} \quad (17)$$

$$\frac{\partial \frac{\partial Q_k}{\partial \delta_k}}{\partial \delta_k} = V_G V_k(-G_{kG}sin(\delta_k) + B_{kG}cos(\delta_k)) = \frac{\partial P_k}{\partial \delta_k} \quad (18)$$

$$\frac{\partial \frac{\partial P_k}{\partial V_k}}{\partial \delta_k} = V_G(-G_{kG}sin(\delta_k) + B_{kG}cos(\delta_k)) = \frac{\frac{\partial P_k}{\partial \delta_k}}{V_k} \quad (19)$$

Now, applying these terms of Equations (16) – (18) in Equation (15), we have

$$\frac{\partial J_D}{\partial \delta_k} = \frac{\partial Q_k}{\partial \delta_k}\left[\frac{1}{V_k}\frac{\partial P_k}{\partial \delta_k} - \frac{\partial Q_k}{\partial V_k}\right] - \frac{\partial P_k}{\partial \delta_k}\left[\frac{1}{V_k}\frac{\partial Q_k}{\partial \delta_k} + \frac{\partial P_k}{\partial V_k}\right] \quad (20)$$

Similarly, the term $\frac{\partial J_D}{\partial V_k}$ can be expressed as

$$\frac{\partial J_D}{\partial V_k} = \left[\frac{\partial P_k}{\partial \delta_k}\frac{\partial \frac{\partial Q_k}{\partial V_k}}{\partial V_k} + \frac{\partial Q_k}{\partial V_k}\frac{\partial \frac{\partial P_k}{\partial \delta_k}}{\partial V_k}\right] - \left[\frac{\partial P_k}{\partial V_k}\frac{\partial \frac{\partial Q_k}{\partial \delta_k}}{\partial V_k} + \frac{\partial Q_k}{\partial \delta_k}\frac{\partial \frac{\partial P_k}{\partial V_k}}{\partial V_k}\right] \quad (21)$$

Again, utilizing Equations (8) to (11), we have

$$\frac{\partial \frac{\partial Q_k}{\partial V_k}}{\partial V_k} = -2B_{kk} \quad (22)$$

$$\frac{\partial \frac{\partial P_k}{\partial \delta_k}}{\partial V_k} = V_G(-G_{kG}sin(\delta_k) + B_{kG}cos(\delta_k)) = \frac{\frac{\partial P_k}{\partial \delta_k}}{V_k} \quad (23)$$

$$\frac{\partial \frac{\partial Q_k}{\partial \delta_k}}{\partial V_k} = V_G(G_{kG}cos(\delta_k) + B_{kG}sin(\delta_k)) = \frac{\frac{\partial Q_k}{\partial \delta_k}}{V_k} \quad (24)$$

$$\frac{\partial \frac{\partial P_k}{\partial V_k}}{\partial V_k} = 2G_{kk} \quad (25)$$

Processing Equation (9) and Equation (10), $\mathbf{G_{kk}}$ can be expressed as

$$G_{kk} = \frac{1}{2V_k}\left[\frac{\partial P_k}{\partial V_k} - \frac{1}{V_k}\frac{\partial Q_k}{\partial \delta_k}\right] \quad (26)$$

Processing Equation (8) and Equation (11), $\mathbf{B_{kk}}$ can be expressed as

$$B_{kk} = -\frac{1}{2V_k}\left[\frac{\partial Q_k}{\partial V_k} + \frac{1}{V_k}\frac{\partial P_k}{\partial \delta_k}\right] \quad (27)$$

Now, applying values of Equations (22), (23), (24), (25), (26) and (27) in Equation (21) we have

$$\frac{\partial J_D}{\partial V_k} = \frac{\partial P_k}{\partial \delta_k}\left[\frac{1}{V_k}\left[\frac{\partial Q_k}{\partial V_k} + \frac{1}{V_k}\frac{\partial P_k}{\partial \delta_k}\right] + \frac{1}{V_k}\frac{\partial Q_k}{\partial V_k}\right] - \frac{\partial Q_k}{\partial \delta_k}\left[\frac{1}{V_k}\frac{\partial P_k}{\partial V_k} + \frac{1}{V_k}\left[\frac{\partial P_k}{\partial V_k} - \frac{1}{V_k}\frac{\partial Q_k}{\partial \delta_k}\right]\right] \quad (28)$$

The terms $\frac{\partial P_k}{\partial \delta_k}$, $\frac{\partial P_k}{\partial V_k}$, $\frac{\partial Q_k}{\partial \delta_k}$ and $\frac{\partial Q_k}{\partial V_k}$ of Equations (20) and (28) are the elements of the modified Jacobian matrix of a multibus system represented by Equation (3) and $\mathbf{V_k}$ is the bus voltage of the kth target bus. Now, to relate change in real power injection at target kth bus to the change in determinant of the modified Jacobian matrix of a multibus system, variables $\mathbf{\Delta\delta_k}$ and $\mathbf{\Delta V_k}$ of Equation (13) are replaced by $\mathbf{\Delta P_k}$ and $\mathbf{\Delta Q_k}$ as follows:

$$\begin{aligned}\Delta J_D &= \begin{bmatrix} \frac{\partial J_D}{\partial \delta_k} & \frac{\partial J_D}{\partial V_k} \end{bmatrix} \begin{bmatrix} \frac{\partial P_k}{\partial \delta_k} & \frac{\partial P_k}{\partial V_k} \\ \frac{\partial Q_k}{\partial \delta_k} & \frac{\partial Q_k}{\partial V_k} \end{bmatrix}^{-1} \begin{bmatrix} \Delta P_k \\ \Delta Q_k \end{bmatrix} \\ &= f_1\Delta P_k + f_2\Delta Q_k \\ &= f_1\Delta P_k + f_2 tan\phi_k \Delta P_k \quad \text{;for load pf same} \\ &= (f_1 + f_2 tan\phi_k)\Delta P_k = f\Delta P_k \end{aligned} \quad (29)$$

The system collapse occurs when J_D becomes zero. Now, if $\mathbf{J_D^o}$ is the determinant value corresponding to the defined operating condition of the system, then the required change in $\mathbf{\Delta J_D}$ of Equation(29) is $\mathbf{\Delta J_D = 0 - J_D^o}$ and corresponding change in injection at kth bus will be

$$\Delta P_k = \frac{-J_D^o}{f} \quad (30)$$

Therefore, load margin at kth load bus, i.e., the additional load that can be supplied to the kth load bus to push it to the proximity of voltage collapse is:-

$$P_{Dk}^{margin} = -\Delta P_k = \frac{J_D^o}{f} \quad (31)$$

Therefore, predicted critical load for kth load bus at the point of voltage collapse is:-

$$P_{Dk}^{predt} = P_{Dk} + P_{Dk}^{margin} \quad (32)$$

But, $\mathbf{P_{Dk}^{margin}}$ is determined using linear relation between $\mathbf{\Delta J_D}$ and $\mathbf{\Delta P_k}$. As such, load margin for the kth load bus $\mathbf{P_{Dk}^{margin}}$ would be more than the actual load margin of the bus. Further, for wide change in $\mathbf{\Delta J_D}$ the predicted load value

will be considerably high compared to that of actual critical load value at the point of voltage collapse. Therefore, it is required to confirm the actual load margin or critical load of a load bus through an iterative load flow analysis using the load margin determined by the Equation (31).

To ensure convergence of the load flow analysis in the proposed iterative procedure, the predicted critical load value $\mathbf{P_{Dk}^{margin}}$ is normalized in such a way that the modified predicted critical load value remains below the actual critical load of the bus. For this purpose, a reduction factor (**RF**) and a distance factor (**DF**) are used to normalize the predicted critical load value for the kth load bus as follows:

$$P_{Dk}^{crt} = P_{Dk} + \frac{RF}{DF} P_{Dk}^{margin} \qquad (33)$$

The distance factor (**DF**) will be higher, when prediction is done for wide change of $\mathbf{\Delta J_D}$, i.e., far from the proximity of voltage collapse limit. Thus, it will normalize the effect of over prediction due to wide change of $\mathbf{\Delta J_D}$. Therefore, as the iterative procedure approaches, the proximity of voltage collapse limit $\mathbf{P_{Dk}^{margin}}$ will become very small; thus, the term $\frac{P_{Dk}+P_{Dk}^{margin}}{P_{Dk}}$ will also approach 1. When the value of $\mathbf{J_D}$ becomes very small (say 0.0001 or less), the iterative procedure has to be terminated.

IV. PROCEDURE FOR DISTRIBUTION OF NORMALIZED PREDICTED LOAD MARGIN TO THE GENERATORS

In a practical system, the increase in load at a bus is contributed by more than one generator. Therefore, it is proposed to redistribute the normalized predicted load margin $\left[\frac{RF}{DF} P_{Dk}^{margin}\right]$ of the kth target bus among the generators using their moment of inertia as the basis. Therefore, expression for the modified generation of ith generator is as follows:

$$P_{Gi}^{K+1} = P_{Gi}^{K} + \frac{H_i}{\sum_{j=1}^{NG} H_j}\left[\frac{RF}{DF} P_{Dk}^{margin}\right] \quad \text{for} \quad i = 1 \ldots NG \ (35)$$

, subjected to the limiting constraints

$$P_{Gi} \le P_{Gi}^{max} \quad \text{for} \quad i = 1 \ldots NG \qquad (36)$$

, where- $\mathbf{H_i}$ and $\mathbf{P_{Gi}^{max}}$ are the moment of inertia and the maximum limit on generation for ith generating station, respectively. K is the iteration count.

V. ALGORITHM OF THE ITERATIVE PROCEDURE

Reduction factor (**RF**) is used to normalize the over prediction of load margin (which is determined using linear relation between $\mathbf{\Delta P_{Dk}^{margin}}$ and $\mathbf{\Delta J_D}$ governed by Equation (29) with the objective of ensuring convergence of load flow analysis used in the proposed iterative procedure. As such, load at a bus must be always less than actual critical load of the bus, i.e. to say that P_{Dk}^{crt} determined using Equation (33) must be less than actual critical load of the bus. In case, P_{Dk}^{crt} determined using Equation (33) becomes slightly more than actual critical load of the bus (due to improper selection of Reduction Factor (**RF**), the load flow analysis of the iterative procedure will not converge. To take into account of such a situation, the proposed algorithm is equipped with a step after the load flow analysis. This step reloads the loads and generations of the system of the previous iteration values and reduces the reduction factor (**RF**) as **RF** = 1/1.5 and load flow analysis is carried out again before proceeding to the other portion of the algorithm. This step helps in changing the value of reduction factor (**RF**) to ensure proper normalization (by Reduction Factor (**RF**)) of critical load governed by Equation (20). The algorithm of the proposed iterative procedure is as follows:-

1. Initialize the load flow data for the system and set iteration count **K** = 0, **RF** = (0.3 to 0.5).
2. Initialize the bus voltages **[V]** and angles **[δ]** and conduct load flow analysis of the system.
3. Check for load flow convergence criteria. If load flow has converged, then go to Step-4. Otherwise, reduce reduction factor **RF** = 1/1.5 and reload $P_{Dk}^{K+1} = P_{Dk}^{K}$, and $Q_{Dk}^{K+1} = Q_{Dk}^{K}$. Also the generating stations output with their Kth iteration values and go to Step-2
4. Determine P_{Dk}^{crt} using Equation (33) and assign $P_{Dk}^{K+1} = P_{Dk}^{crt},\ Q_{Dk}^{K+1} = tan\phi_k P_{Dk}^{K+1}$
5. Distribute the additional load $\frac{RF}{DF} P_{Dk}^{margin}$ among the generating stations based on defined criteria subjected to generation limits of the generating stations as described in Section IV. In case of reactive power limit violation, a PV bus has to be changed into a PQ bus by assigning reactive power at its limit.
6. Check for $|J_D| < \epsilon(= 0.0001)$, go to Step 7. If not, set **K** = **K + 1** and go to Step 2.
7. Stop.

VI. SIMULATION, RESULTS AND DISCUSSIONS

To verify the validity and applicability of the proposed method, simulations were carried out on IEEE 30 and IEEE 118 bus systems. The proposed algorithm is used to determine critical load of a bus with different reduction factors (**RF**). It has been found that **RF** value between 0.1 to 0.5 ensure convergence of load flow analysis in the iterative process for IEEE 30 and IEEE 118 bus systems for any target

bus of the system. But, with **RF** = 0.3 to 0.5, the iterative procedure terminates with less number of iterations. During iteration, the additional load assigned on the target (k) bus was distributed among all the generating stations based on their load contribution (subjected to their limits) as described in Section 3. Continuation power flow analysis technique is also used to determine the critical load at the target buses with step size **σ** = 0.001, because the correction load flow does not converge for step size greater than 0.001.

Table 1 represents the simulation results for some of the buses of IEEE 30 bus system with **RF** = 0.5 with power factor 0.8. Table 2 represents the simulation results for some of the buses of IEEE 118 bus system with **RF** = 0.5 with power factor 0.8.

Table 1: Critical load of some of the buses(k) of IEEE 30 bus system for load pf 0.8.

k	Initial			proximity to collapse				
	J_D	$\Delta\lambda$	P_{Dk}	J_D	$\Delta\lambda$	P_{Dk}	CPU Time(in ms)	Remarks
3	168.33	-	0.224	-0.046	-	3.549	120.0	PM
3	-	34.981	0.224	-	-0.039	3.549	470.0	CLF
7	110.381	-	0.328	-0.045	-	3.640	110.0	PM
7	-	32.399	0.328	-	-0.023	3.640	570.0	CLF
12	49.18	-	0.112	-0.038	-	2.271	120.0	PM
12	-	32.666	0.112	-	-0.060	2.271	500.0	CLF
18	9.121	-	0.032	-0.002	-	0.729	120.0	PM
18	-	13.014	0.032	-	-0.010	0.729	540.0	CLF
24	13.283	-	0.027	-0.018	-	0.918	150.0	PM
24	-	16.348	0.027	-	-0.027	0.918	557.0	CLF
29	1.937	-	0.034	-0.000	-	0.312	80.0	PM
29	-	11.401	0.034	-	-0.014	0.312	410.0	CLF

Table 2: Critical load of some of the buses(k) of IEEE 118 bus system for load pf 0.8.

k	Initial			proximity to collapse				
	J_D	$\Delta\lambda$	P_{Dk}	J_D	$\Delta\lambda$	P_{Dk}	CPU Time(in ms)	Remarks
55	536.445	-	0.630	-0.074	-	10.946	3730.0	PM
55	-	59.444	0.630	-	-0.002	10.946	6780.0	CLF
76	96.6729	-	0.680	-0.109	-	2.499	2500.0	PM
76	-	7.062	0.680	-	-0.002	2.499	6240.0	CLF
104	114.078	-	0.380	-0.010	-	4.564	3040.0	PM
104	-	25.838	0.380	-	-0.003	4.564	7070.0	CLF
60	1231.221	-	0.780	-0.236	-	20.870	3470.0	PM
60	-	103.763	0.780	-	-0.001	20.870	7020.0	CLF
88	102.643	-	0.480	-0.143	-	4.153	3600.0	PM
88	-	18.760	0.480	-	-0.001	4.153	6800.0	CLF
45	88.449	-	0.530	-0.025	-	3.025	3320.0	PM
45	-	16.135	0.530	-	-0.002	3.025	6700.0	CLF
118	141.844	-	0.330	-0.155	-	2.641	2700.0	PM
118	-	8.235	0.330	-	-0.001	2.641	6120.0	CLF

PM repesents proposed method and CLF represents continuation load flow.

Tables represent the target bus selected for determination of critical load with respect to its voltage collapse limit, initial value of two by two Jacobian matrix for the target bus, initial value of predicted continuation parameter (**Δλ**), initial load at the target bus, final value of two by two Jacobian matrix, final value of predicted continuation parameter (at the point of collapse), critical load for the target bus and remarks about the methods.

It is observed that J_D value of two bus equivalent system of IEEE 30 and IEEE 118 bus systems have different initial values for different target buses, as such, $\mathbf{J_D}$ value for a bus reflects the voltage stability characteristic of the bus.

It has been observed that the distance factor **DF** = $\left(\frac{P_{Dk}+P_{Dk}^{margin}}{P_{Dk}}\right)$ becomes very close to 1, when the iterative process terminates. But, at the beginning of the iterative process it appears to be high depending upon change of ΔJD used for the prediction of load margin for the load bus. It normalizes the effect of over prediction of load margin due to wide change of ΔJD and ensures convergence of the load flow analysis of the system during the iterative process.

The programs were executed on a P C with Pentium-4 processor having processor speed of 1.5 GHz and LINUX operating system. The simulation results show that the proposed method requires considerably less CPU time compared to that of continuation power flow analysis. Continuation power flow analysis requires on an average 2(Approx.) times more CPU time than that of proposed method.

VII. CONCLUSION

The paper proposed an algorithm for voltage stability analysis of a target/selected load bus using the singularity condition of the load flow Jcaobian matrix. Network partitioning technique is used to transform load flow Jocobian matrix into a two by two matrix with respect to a selected/target bus. It is observed that determinant value of two bus equivalent system of IEEE 30 and IEEE 118 bus system have different initial values for different target buses, as such, it shows that the transformed two by two elements Jacobian matrix reflects the property/quality of the target bus.

The algorithm proposed for the determination of critical load of a bus with respect to its voltage collapse limit of a power system works for all buses of IEEE 30 and IEEE 118 bus systems, as such, it could be used for any inter connected power system. The use of reduction factor (**RF**) and distance factor (**DF**) ensures convergence of the load flow analysis of the system during the proposed iterative procedure. These two factors effectively normalize the prediction of load margin, which is carried out using the linear relation between $\mathbf{\Delta J_D}$ and $\mathbf{\Delta P_k}$ governed by equation (33). The simulation results show that the proposed method requires considerably less CPU time compared to that of continuation power flow analysis.

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